Why the NMSSM?
Low-energy phenomenology and possible signatures at the LHC

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Do we need to go beyond the Standard Model?

Looking for a theory that describes Nature as we perceive it...

⇒ **Observation:**

- massive **neutrinos**
- **matter** - antimatter asymmetry
- **dark** matter

⇒ **Theoretically:**

EWSB mechanism: the Higgs (yet to be discovered!)

the **hierarchy problem** m_H^2 only SM dimensionful parameter

$\Delta m_H^2 \propto g^2/16\pi^2 \Lambda_{\text{UV}}^2$ **not "protected"!**

Understand the SM: gauge group, flavour, CPV, mass generation ...

E.g. gauge couplings $g_1 : g_2 : g_3$ (GUT?)

4 fundamental interactions: inclusion of gravity?

$\Lambda_{\text{QCD}} \leftrightarrow M_{\text{EW}} \longleftarrow - - - - - - \longrightarrow M_{\text{Planck}}$ **the desert?**

Extending the Standard Model

Any "candidate" model /theory should, ideally:

★ **Explain** experimental **observation;**

★ **Solve** (or at least improve) **SM** theoreticall **issues;**

★ **Testable** (allow for a dialogue with experiment!)

Profit from a **unique era!** (LHC, flavour dedicated, dark matter, Planck, etc..)

Beyond the SM: several appealing, well motivated possibilities (from A to Z):

Extended Gauge Groups; Extra dimensions; GUTs; Little Higgs;

String theory; **Supersymmetry**; ...

From the SM to the cNMSSM: plan

- **SUSY on a nutshell**

  Minimimal SUSY extension of the SM

- **The NMSSM:** Introduction

  Illuding detection at LEP

  Aspects of low energy phenomenology

- **NMSSM from supergravity:** Allowed parameter space

  Higgs and sparticle mass spectra

  cNMSSM at colliders

- **Outlook**

Motivating Supersymmetry

SUSY on a nutshell

Symmetry that relates **Bosons** and **Fermions**, **Forces** and **Matter**

Introduces **new Particles**: 2 **Higgs** doublets (H_u, H_d) $[\tan\beta = v_u/v_d]$

and **superpartners** for *all* particles

Broken symmetry: $m_{\tilde{e}} \neq m_e$

Motivating SUSY

- Elegant solution to the **hierarchy** problem

  If SUSY is softly broken $\Delta m_H^2 \propto M_{\text{SUSY}}^2 (\frac{\lambda}{16\pi^2} \log \frac{\Lambda_{\text{UV}}}{M_{\text{SUSY}}})$

- Radiative **spontaneous electroweak symmetry** breaking

  At M_{EW}, one **"naturally"** has $m_{H_u}^2 < 0$ (if $m_t \gtrsim 70$ GeV)

- **Unification** of the **gauge couplings** (around 10^{16}GeV)

- If R-parity conserving: neutral, colourless, stable **L**ightest **S**USY **P**article

  $\Rightarrow$ candidates for **cold dark matter**

- SUSY versions of mechanisms for **ν-mass generation** and **leptogenesis**

- Inclusion of **gravity** with **local SUSY??**

Minimal SUSY extension of the SM (MSSM)

Superfield $\hat{\phi}$ $\begin{pmatrix} \text{SM particles} \\ \text{super-partners} \end{pmatrix}$ Δ spin $= \frac{1}{2}$ **same quantum #'s** **same interactions**

$$\begin{pmatrix} \text{fermions} \\ \text{scalars} \end{pmatrix} \leftrightsquigarrow \begin{pmatrix} \text{quarks} & \mathbf{q} \\ \text{squarks} & \tilde{\mathbf{q}} \end{pmatrix} ; \begin{pmatrix} \text{leptons} & \mathbf{l} \\ \text{sleptons} & \tilde{\mathbf{l}} \end{pmatrix} ; \begin{pmatrix} \text{higgsinos} & \tilde{\mathbf{h}}_{\mathbf{u,d}} \\ \text{Higgs} & H_{u,d} \end{pmatrix}$$

$$\begin{pmatrix} \text{gluino} & \tilde{\mathbf{g}} \\ \text{gluon} & \mathbf{g} \end{pmatrix} ; \begin{pmatrix} \text{wino} & \tilde{\mathbf{W}} \\ & \mathbf{W} \end{pmatrix} ; \begin{pmatrix} \text{bino} & \tilde{\mathbf{B}} \\ & \mathbf{B} \end{pmatrix} \leftrightsquigarrow \begin{pmatrix} \text{fermions} \\ \text{gauge bosons} \end{pmatrix}$$

Physical states: **Squarks, sleptons, gluinos**

Charginos: {winos, charged higgsinos} $\rightarrow \tilde{\chi}^{\pm}_{1,2}$

Neutralinos: {bino, w^0-ino, neutral higgsinos} $\rightarrow \tilde{\chi}^{0}_{1-4}$

Higgs: {CP-even, CP-odd, charged} $\rightarrow h^0,\ H^0,\ A^0,\ H^{\pm}$

Rich low-energy spectrum, potentially observable at the LHC!

Minimal SUSY extension of the SM (II):

★ **Superpotential:** $W = \; Y_u\, \hat{H}_u\, \hat{Q}\, \hat{u} + Y_d\, \hat{H}_d\, \hat{Q}\, \hat{d} + Y_e\, \hat{H}_d\, \hat{L}\, \hat{e}$ - $\boldsymbol{\mu}\, \hat{H}_u \hat{H}_d$

$$\Rightarrow \quad \mathcal{L} \subset Y_u H_u Q u + Y_d H_d Q d + Y_e H_d L e - \boldsymbol{\mu}\, \tilde{h}_u \tilde{h}_d + \ldots$$

★ **Soft-breaking terms**:

$$-\mathcal{L}_{\mathsf{SOFT}} = \boldsymbol{m^2_{H_u}}\, H_u^*\, H_u + \boldsymbol{m^2_{H_d}}\, H_d^* H_d + (\boldsymbol{B\mu} H_u H_d + \text{H.c.})$$

$$+ (\boldsymbol{M_i}\, \psi_i \psi_i + \text{H.c.}) + \boldsymbol{m^2_{\tilde{F}}}\, \tilde{F}\, \tilde{F}^* + \boldsymbol{A_F Y_F} H_i\, \tilde{F}\, \tilde{F}^* + \ldots$$

★ **Two upsetting issues:**

⇒ Origin & nature of **SUSY breaking??**

⇒ **μ-problem** - a **mass term** in W, not related to **SUSY breaking**

remarkable **exception** to **fermion mass** generation ...

SUSY (& MSSM) issues: SUSY breaking

LEP constraints $\Rightarrow$ **"not so light" SUSY scale**

Flavour physics and CP violation (K's, B's, EDM's, ...)

$\Rightarrow$ **Flavour blind** mechanism of SUSY breaking

Spontaneous SUSY breaking generates soft-SUSY breaking terms all proportional to a common scale (M_{SUSY})

Supergravity mediated
Gauge mediation
$\Rightarrow$ flavour blind (universal), CP conserving, SUSY soft breaking terms! (at corresponding mass scale)

cMSSM (mSUGRA-like): (Universal) boundary conditions $\leftrightsquigarrow$ **c** = "constrained"

$$M_i = M_{1/2}; \quad (M_0^{\tilde{\phi}})_{ij} = M_0 \quad ; \quad (A_0^{\tilde{\phi}})_{ij} = A_0$$

at a common scale, **gauge-coupling unification scale**, $M_X \approx 10^{16}$ **GeV**

SUSY (& MSSM) issues: the μ problem

★ **SUSY conserving** mass term for Higgses in $W = \mu \hat{H}_u \hat{H}_d$

⋆ MSSM: minimisation of the scalar **potential** (EW symmetry breaking)

$$\Rightarrow M_Z^2 = M_Z^2(m_{H_u}^2, m_{H_d}^2, \mu^2)$$

$$m_{H_u}, m_{H_d}, \mu \;:\; \mathcal{O}(10 - 100) \times M_Z \quad \rightsquigarrow \quad \mu \lesssim \mathcal{O}(M_{\text{SUSY}})$$

⋆ **LEP constraints** on $\tilde{\chi}^{\pm}$ (wino/higgsino) mass: $\rightsquigarrow$ $\mu \gtrsim 100$ **GeV**

Two **"natural"** values for μ:
- 0 (experimentally excluded)
- typical scale of theory (M_{Planck}, M_{GUT})

Are there other possibilities??

The Next-to-Minimal Supersymmetric Standard Model

By adding a **singlet** superfield $\hat{S}$ to the **MSSM** $\Rightarrow$ **NMSSM**

★ **Elegant solution to the μ-problem of the MSSM**

$$\mu \hat{H}_u \hat{H}_d \quad \rightarrow \quad \lambda \hat{S} \hat{H}_u \hat{H}_d$$

$\Rightarrow$ Only **dimensionless couplings** in W; "Yukawa-like" $\lambda \tilde{h}_u \tilde{h}_d S$ term in $\mathcal{L}$

$\Rightarrow$ **dynamically generated μ:** $\langle S \rangle \sim \mathcal{O}(M_{\text{SUSY}}) \rightsquigarrow$ $\mu_{\text{eff}} = \lambda \langle S \rangle$

$\Rightarrow$ **Scale-invariant superpotential: EW, SUSY scale only** appearing via $\mathcal{L}_{\text{soft}}$

★ **NMSSM**

$\rightsquigarrow$ **Simplest** extension of the SM where the **only scale** is M_{SUSY}

$\rightsquigarrow$ **Original SUSY/SUGRA** extensions of the SM of this type [Fayet, Nilles, ...]

NMSSM new features: an introduction

$$W = Y_u \hat{H}_u \hat{Q} \hat{u} + Y_d \hat{H}_d \hat{Q} \hat{d} + Y_e \hat{H}_d \hat{L} \hat{e} - \boldsymbol{\lambda} \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \boldsymbol{\kappa} \hat{S}^3$$

$$-\mathcal{L}_{\text{soft}}^{\text{Higgs}} = m_{H_i}^2 H_i^* H_i + \boldsymbol{m_S^2} S^* S + \left(-\boldsymbol{\lambda} \boldsymbol{A_\lambda} S H_u H_d + \frac{1}{3} \boldsymbol{\kappa} \boldsymbol{A_\kappa} S^3 + \text{H.c.} \right)$$

Neutralino sector:
- 5 Majorana fermions (χ^0_{1-5})
- $\tilde{\chi}^0_1 = N_{11} \tilde{B}^0 + N_{12} \tilde{W}^0_3 + N_{13} \tilde{H}^0_d + N_{14} \tilde{H}^0_u + \boldsymbol{N_{15}} \tilde{\boldsymbol{S}}$

Neutral Higgs sector:
- 2 pseudoscalar (a^0_1, a^0_2) and 3 **scalar bosons** (h^0_1, h^0_2, h^0_3)
- $h^0_1 = S_{11} H^0_d + S_{12} H^0_u + \boldsymbol{S_{13}} \boldsymbol{S}$

$\Rightarrow$ **NMSSM: Richer, more complex phenomenology**

LEP and the NMSSM

★ **Little fine tuning problem** (**non-observation** of Higgs at LEP)

Theoretically.. MSSM @ tree-level: $m_{h_1^0} \lesssim M_Z |\cos 2\beta|$

RC $^{(t-\tilde{t})}$: $m_{h_1^0}^{\text{CMSSM}} \lesssim 125$ GeV; $m_{h_1^0}^{\text{MSSM}} \lesssim 135$ GeV

Experimentally.. $m_{h_1^0}^{\text{LEP}} \gtrsim 114$ GeV

A narrow window for $m_{h_1^0}$...

★ In the NMSSM **less severe** "Higgs - little fine tuning problem"

Theoretically higher upper bound on $m_{h_1^0}$

Additional contributions to $m_{h_1^0}$, low $\tan\beta$ regime $\Rightarrow m_{h_1^0} \sim 145$ GeV

Experimentally "invisible" h_1^0 (escaped LEP detection)

$\Rightarrow$ **Enlarge window for $m_{h_1^0}$!**

NMSSM Higgs: Illuding detection - LEP (un)signatures

$\Rightarrow$ NMSSM light Higgs ($m_{h_1^0} \lesssim 114$ GeV) **are still allowed by LEP data:**

(i) $\boldsymbol{Z - Z - h_1^0}$ coupling is heavilly **suppressed**

$\rightsquigarrow$ **singlet** dominated $\boldsymbol{h_1^0}$

$\rightsquigarrow$ SM-like $\boldsymbol{h_2^0}$ **relatively light** (but ~ 15 GeV heavier than in MSSM!)

[Ellwanger, Hugonie]

(ii) $\boldsymbol{m_{a_1^0} \lesssim 11}$ **GeV** * allowing for $m_{h_1^0} \sim 86$ GeV

$\rightsquigarrow$ SM-like $\boldsymbol{h_1^0}$ dominant **decay** $\boldsymbol{h_1^0 \to a_1^0\, a_1^0}$

$\rightsquigarrow$ **Forbidden** $a_1^0 \to b\,\bar{b}$, only $h_1^0 \to a_1^0\, a_1^0 \to 4\,\tau$

*constraints from B-physics [Domingo, Ellwanger '07]

$\Rightarrow$ NMSSM: Constraints from LEP are easier to satisfy

Less fine-tuning required ! [Dermisek, Gunion, Bastero-Gil, ...]

The general NMSSM: LHC detection prospects

★ Depending on the regime (especially λ, $\tan\beta$) **many possible scenarios...**

⇒ **Disentangling MSSM - NMSSM Higgs** Ellwanger, Gunion, Hugonie, Moretti, ...

- large λ $\begin{cases} \text{more visible Higgs and/or } \chi^0 \\ \text{observable, unconventional Higgs and } \tilde{\phi} \text{ decays, eg. } h_1^0 \to a_1^0\, a_1^0 \end{cases}$
- small λ - more difficult...

★ **Phenomenological studies and experimental analysis/simulations required!**

2008: NMSSM benchmark proposal [Djouadi et al$|_{\text{AMT}}$, '08]

⇒ **5 distinct, representative low-energy NMSSM scenarios**

light singlet like h_1^0; dominant SM-like $h_1^0 \to a_1^0\, a_1^0$; quasi-degenerate Higgses...

NMSSM Tool Box

NMSSMTools

Ellwanger, Hugonie

- Low-energy inputs
- Scenarios for SUSY breaking (SUGRA, GMSB)
- Sparticle and Higgs spectra: masses & couplings
- BRs Higgs decays
- Constraints from LEP, Tevatron on $m_{\tilde{\phi}}$
- LEP constraints (even unusual decay channels) on Higgses
- B-physics and $(g-2)_\mu$

http://www.th.u-psud.fr/NMHDECAY/nmssmtools.html

Link to **MicrOMEGAs 2.2:** Dark matter analysis

Belanger et al (relic density; direct and indirect detection)

NMSSM and soft SUSY breaking mechanisms

All previous features emerge in "generic", unconstrained NMSSM formulation; strongly dependent on the choice of $\mathcal{L}_{\rm soft}$

$$\star\ -\mathcal{L}_{\rm soft} = m^2_{H_i}\, H_i^* H_i + m_S^2\, S^* S + \left(-\lambda\, A_\lambda S H_u H_d + \tfrac{1}{3}\kappa\, A_\kappa\, S^3 + \text{H.c.}\right)$$
$$+ \left(M_i\, \psi_i \psi_i + \text{H.c.}\right) + m^2_{\tilde{F}_{ij}}\, \tilde{F}_i\, \tilde{F}_j^* + \ldots$$

SUSY breaking mechanisms $\leftrightsquigarrow$ universal boundary conditions at high scale

$\Rightarrow$ **NMSSM from gauge mediated SUSY breaking**

[recent: Delgado, Giudice, Slavich '07; Giudice, Kim, Rattazzi '07; Ellwanger, Jean-Louis, AMT '08; Liu, Wagner '08]

$\Rightarrow$ **Minimal supergravity inspired NMSSM**

[Ellwanger, Rausch de Traubenberg, Savoy '95,'97; Elliot, King, White'95; Djouadi, Ellwanger, AMT 0803.0253 & 0811.2699]

NMSSM with universal soft terms at GUT scale

mSUGRA-like: $M_i = M_{1/2}$; $(m_0^{\tilde{F},\phi})_{ij} = m_0$; $(A_0^{\tilde{F},\phi})_{ij} = A_0$

$$\Rightarrow m_{H_u} = m_{H_d} = m_S = m_0,\ A_\lambda = A_\kappa = A_0$$

cNMSSM: $M_{1/2},\ m_0,\ A_0,\ \lambda,\ \kappa$ $\Rightarrow$ 5 continuous parameters

Analogous to the cMSSM: $M_{1/2},\ m_0,\ A_0,\ \mu,\ B\mu$

⋆ **Practical purposes** (RGE's, numerics, ...) $\kappa \leftrightsquigarrow \tan\beta$

⋆ Requiring correct M_Z $\Leftrightarrow$ $\tan\beta = \tan\beta(M_{1/2},\ m_0,\ A_0,\ \lambda)$

constrained NMSSM: $M_{1/2},\ m_0,\ A_0,\ \lambda$

Constraining the cNMSSM: scalar potential & LEP

★ **Phenomenologically acceptable minimum** of Higgs potential

$$V_{\text{Higgs}} \sim \kappa^2\, s^4 + \tfrac{2}{3}\kappa\, A_\kappa\, s^3 + m_S^2\, s^2 + \ldots$$

⋆ **Non vanishing s:** $\Rightarrow \; m_0 \lesssim \frac{1}{3}|A_0|$

cMSSM: **low m_0** disfavoured (charged slepton LSP)

cNMSSM: **low m_0 required** to generate $< S >$; **singlino LSP**

⋆ **Absence of pseudoscalar tachyons:** $\Rightarrow \; A_\kappa \sim A_0 < 0$

★ **LEP constraints** ⇝ **upper bound** on λ: typically $\Rightarrow \; \lambda \lesssim 0.02$

★ $(g-2)_\mu$: *favours* **low $M_{1/2}$ regime** $M_{1/2} \lesssim 1$ TeV

Constraining the cNMSSM: dark matter

★ **Comply with WMAP constraints on the relic density**

$$0.094 \lesssim \Omega_{\chi_1^0} h^2 \lesssim 0.136 \qquad (\text{at } 2\,\sigma)$$

⋆ **"Assisted" $\tilde{\tau}_1$ annihilation:** nearly **degenerate LSP and NLSP**

$m^2_{\chi S} \sim m^2_{\tilde{\tau}_R}$ $\Rightarrow\ m_0 \lesssim \frac{1}{10} M_{1/2}$ **small/vanishing m_0**

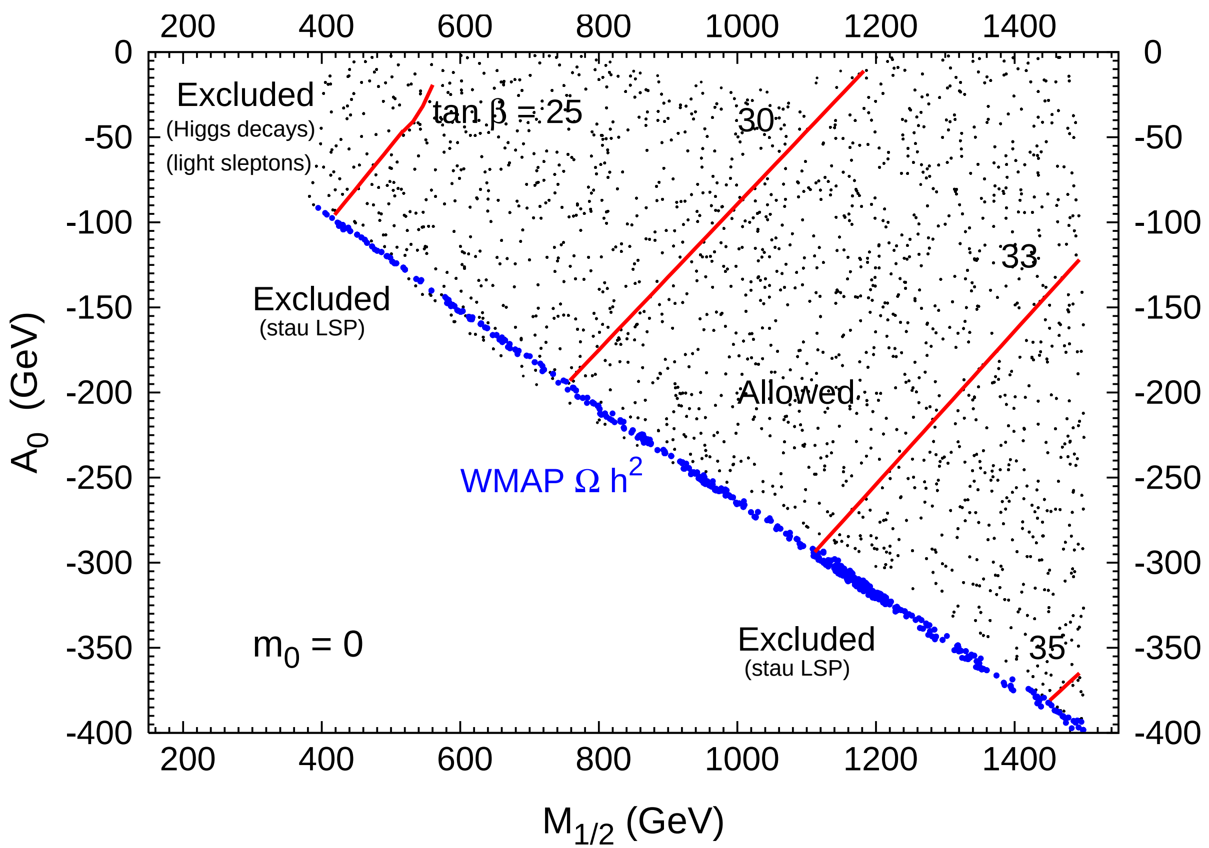
small A_0, determined by $M_{1/2}$ $\Rightarrow\ A_0 \sim -\frac{1}{4} M_{1/2}$

⋆ Diluting LSP density: LSP-NLSP **thermal equilibrium**

for very **small λ** $\rightsquigarrow$ **decoupled** LSP $\Rightarrow\ \lambda \gtrsim 10^{-5}$

⋆ σ_{annih} decreases with $m_{\text{NLSP}} \propto M_{1/2} \Rightarrow M_{1/2}$ not too large ($\lesssim 2-3$ TeV)

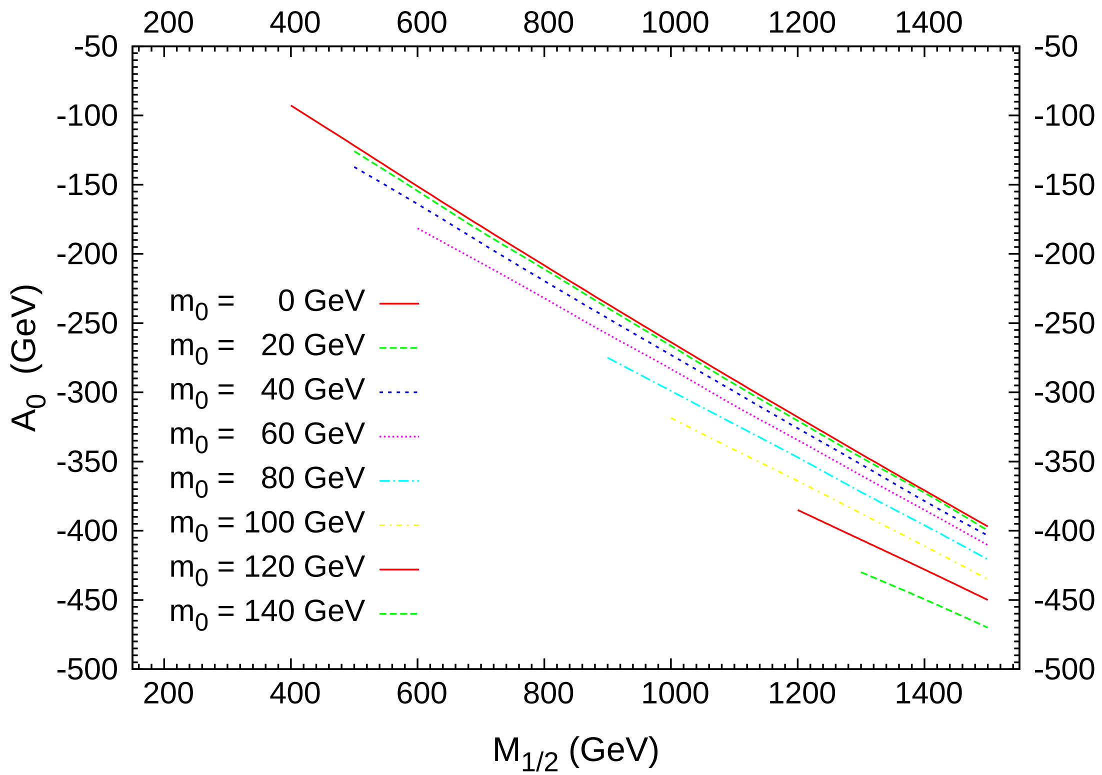
The allowed cNMSSM parameter space



★ **Allowed parameter space: "line" in $[M_{1/2}, A_0]$ plane !**

Small m_0 $\Rightarrow$ cNMSSM: cNMSSM $(M_{1/2})$

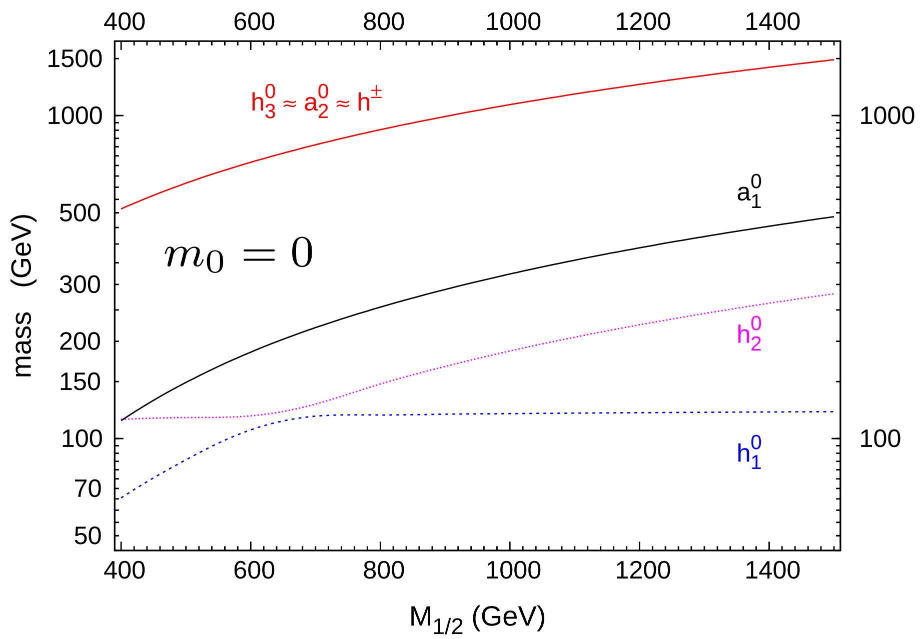
The allowed cNMSSM parameter space

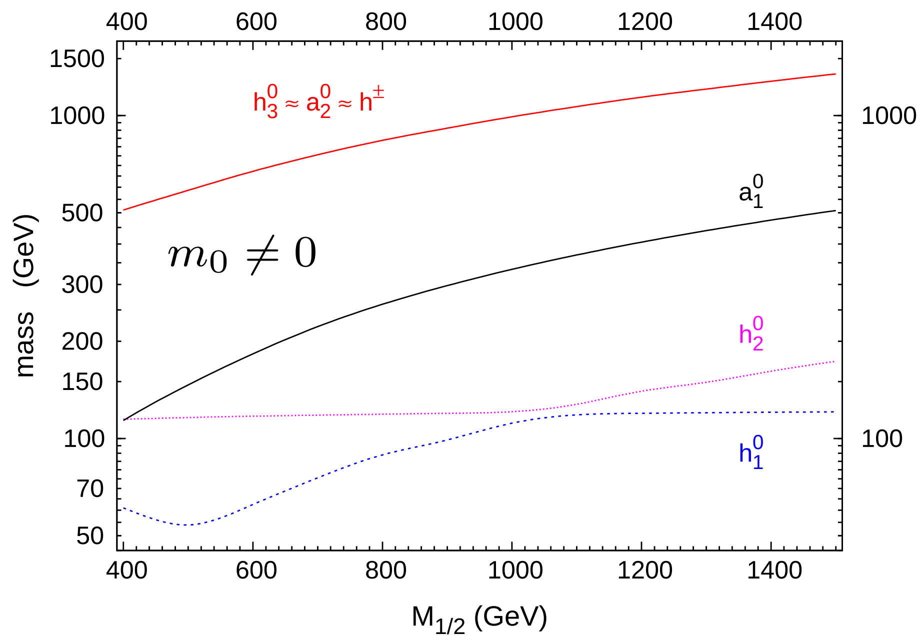


★ **Allowed parameter space: "lines" in $[M_{1/2}, A_0]$ plane !**

Small m_0 $\Rightarrow$ **cNMSSM: cNMSSM ($M_{1/2}$)**

Higgs spectrum





- $M_{1/2} \lesssim \begin{pmatrix} 660 \\ 1100 \end{pmatrix}$ singlet like h_1^0, **SM-like h_2^0** ; $M_{1/2} \gtrsim \begin{pmatrix} 660 \\ 1100 \end{pmatrix}$ **SM-like h_1^0**, singlet like h_2^0

- **"Cross-over":** **small** mass **splitting**; similar **components**; similar couplings

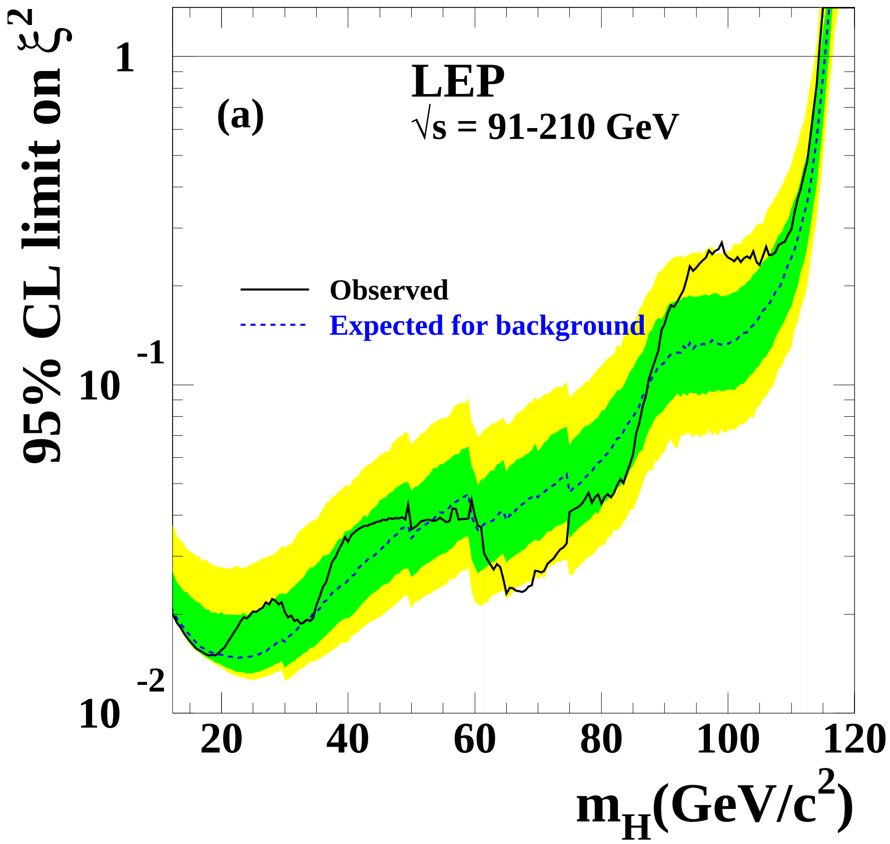
- **Decays:**
  - **SM-like** $h_{1,2}^0$: $b\bar{b}$ (70%) ; BR($h_{1,2}^0 \to \gamma\gamma$) $\approx$ BR$^{\text{SM}}$ $\approx 2 \times 10^{-3}$
  - **Singlet like**: $b\bar{b}$ and $\tau^+\tau^-$ (as well as h_3^0, a_2^0, $h^\pm$)
  - **Higgs-to-Higgs:** possible but NOT typical

Explaining LEP?

Back to LEP2: combined results from all Higgs searches $(e^+ e^- \to h\,Z;\ h \to b\bar{b})$

- ▶ Observed **excesses:** $\begin{cases} m_h \sim \mathbf{115}\ \text{GeV}\ (\mathbf{1.7\sigma}) \\ m_h \sim \mathbf{98}\ \text{GeV}\ (\mathbf{2.3\,\sigma}) \end{cases}$

- ▶ Number of **events** $\sim$ **10%** of $\boldsymbol{h}^{\mathbf{SM}}$ expected



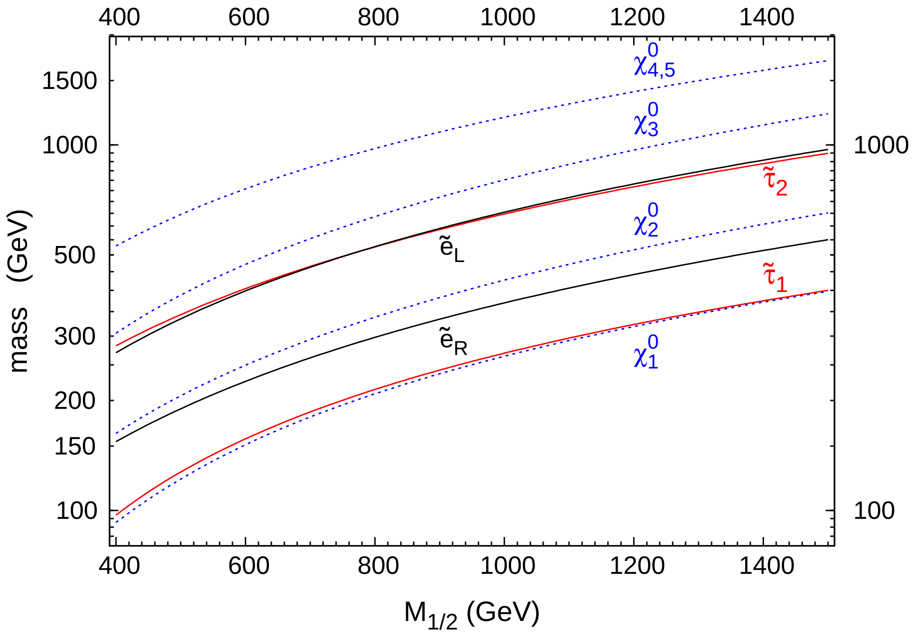
- reduced coupling to SM gauge bosons
  $C_h^V = g_{hZZ}/g_{h^{\rm SM}ZZ} \approx \mathcal{O}(\sqrt{0.1})$
- $C_h^V \sim 1$, but reduced BR$(h \to b\bar{b})$

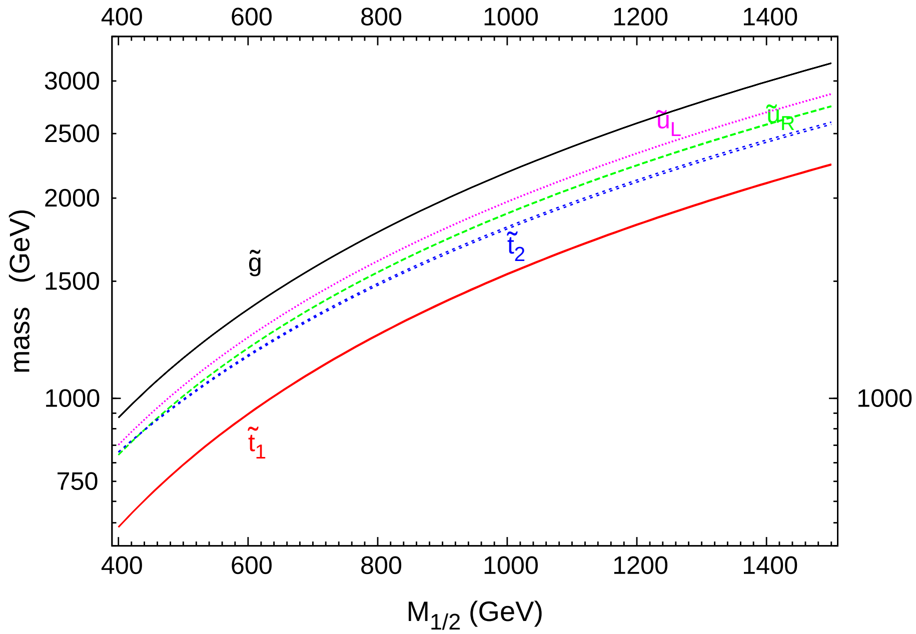
★ **cNMSSM** (cross over regions):

97 GeV $\lesssim m_{h_1^0} \lesssim$ **101 GeV** ; $m_{h_2^0} \approx$ **117 GeV**; $0.28 \lesssim |C^V_{h_1^0}| \lesssim 0.33$

cNMSSM (low $M_{1/2}$): constrained model accounting for LEP!

Sparticle spectrum





- **Neutralino sector:**

  Singlino LSP - nearly degenerate with $\tilde{\tau}_1$

  Bino-like χ_2^0; Wino-like χ_3^0; Higgsino-like $\chi_{4,5}^0$: $\boldsymbol{M_{\chi^0_{4,5}}} \approx \mu_{\rm eff}$

- **Squarks & gluinos:**

  Gluino heavier than all squarks and sleptons (m_0 is small!)

cNMSSM at the LHC: sparticle decay chains

- ⋆ $\tilde{g} \longrightarrow \tilde{q}\, q \qquad (m_{\tilde{g}} \gtrsim m_{\tilde{q}})$

- ⋆ $\tilde{q} \longrightarrow \chi^{0(\pm)}\, q\,(q') \begin{cases} \tilde{q}_L \longrightarrow \chi^0_3\, q \;\; (33\%) \\ \tilde{q}_L \longrightarrow \chi^\pm_1\, q' \;\; (66\%) \end{cases} \qquad \tilde{q}_R \longrightarrow \chi^0_2\, q$

- ⋆ $\tilde{l}_L \longrightarrow \chi^0_2\, l\,; \qquad \tilde{l}_R \longrightarrow l\, \tilde{\tau}_1\, \tau\, (\gtrsim 99\%)$

- ⋆ $\chi^0_3(\chi^\pm_1) \longrightarrow \tilde{l}\, l^{(\prime)}\, (\sim 50\%)\,; \qquad \chi^0_3(\chi^\pm_1) \longrightarrow \tilde{\tau}_1\, \tau\,,\, \tilde{\nu}_\tau\, \nu_\tau\, (\sim 50\%)$

- ⋆ $\chi^0_2 \longrightarrow \tilde{\tau}_1\, \tau$

cNMSSM: Almost all sparticle decay chains contain $\tilde{\tau}_1$ NLSP !

- ⋆ $\tilde{\tau}_1 \longrightarrow \chi^0_1\, \tau\,; \qquad$ **stable** χ^0_1

cNMSSM: **subdominant** cascade decays with **lepton** final states ...

cNMSSM "smoking gun": possibly displaced vertices

cNMSSM: singlino LSP (χ_1^0), mostly right-handed NLSP ($\tilde{\tau}_1$) $\Rightarrow$ **Long-lived $\tilde{\tau}_1$!**

$$\Gamma(\tilde{\tau}_1 \to \chi_1^0 \tau) \approx \lambda^2 \frac{\sqrt{\Delta m^2 - m_\tau^2}}{4\pi m_{\tilde{\tau}_1}} (\alpha \Delta m - \rho\, m_\tau)$$

$\Delta m \equiv m_{\tilde{\tau}_1} - m_{\chi_1^0}$;

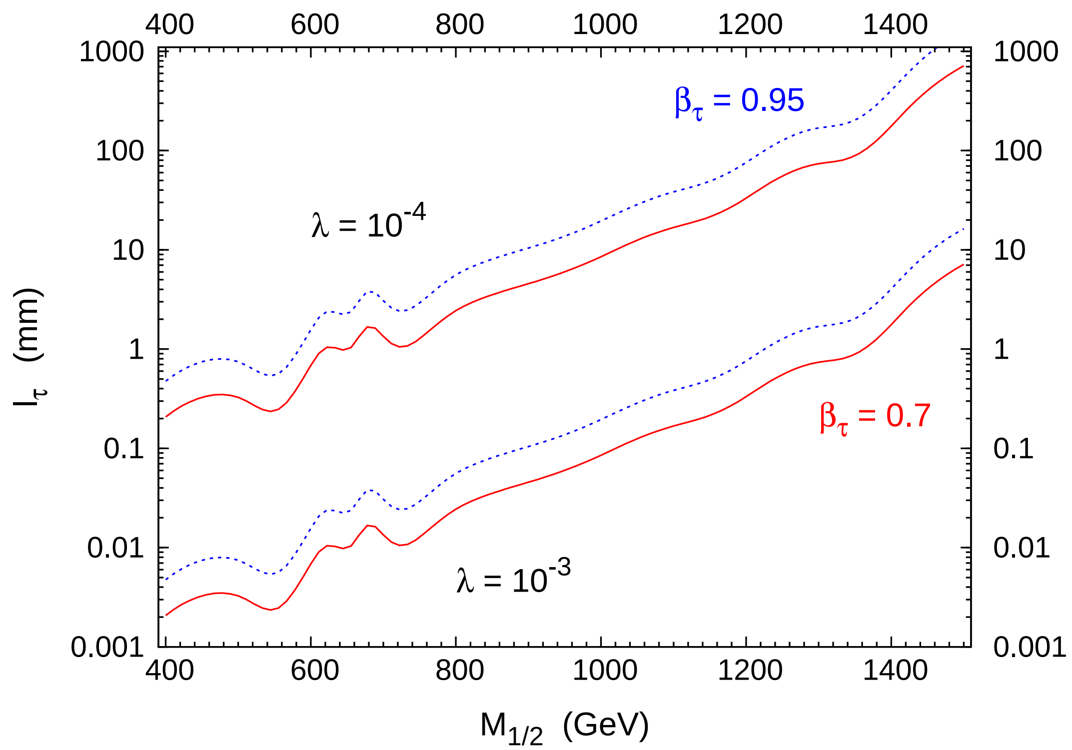
$\alpha(M_{1/2}), \rho(M_{1/2}) \in [10^{-2}, 10^{-4}]$

Realistic $l_{\tilde{\tau}_1}$ in the lab frame

$\Rightarrow \beta_{\tilde{\tau}_1} = v_{\tilde{\tau}_1}/c$ ($\tilde{\tau}_1$ **production**)

$$l_{\tilde{\tau}_1} = \frac{\hbar c}{\Gamma(\tilde{\tau}_1 \to \chi_1^0 \tau)} \sqrt{\frac{\beta_{\tilde{\tau}_1}^2}{1-\beta_{\tilde{\tau}_1}^2}}$$

GMSB ATLAS studies: $\beta_{\tilde{\tau}_1} \gtrsim 0.7$



cNMSSM: $\tilde{\tau}_1$ length of flight $\rightsquigarrow \mathcal{O}$(few centimeters)

cNMSSM prospects for the LHC

Sparticle production:

dominant **production** $\rightsquigarrow$ $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{q}$ and $\tilde{q}\tilde{q}^*$

Low $M_{1/2}$ **regime:** $\sigma \sim 0.5$ pb

$\boldsymbol{\mathcal{L} = 100\ \mathrm{pb}^{-1}} \Rightarrow 10^4 - 10^5$ events

Simplest decay cascade: $\boldsymbol{\tilde{q}_R \to \chi_2^0\, q\,; \quad \chi_2^0 \to \tilde{\tau}_1\, \tau\,; \quad \tilde{\tau}_1 \to \chi_1^0\, \tau}$

3 jets $/\tilde{q}_R$ (one hard quark + 2 τ jets) & long lived $\tilde{\tau}_1$

$\Rightarrow$ complicated measurements of sparticle spectra

Higgs production:

$h_{1,2}^{\text{SM-like}} \rightsquigarrow$ gluon-gluon & vector boson fusion $\quad h_{1,2} \to \gamma\gamma$

heavier Higgses $\rightsquigarrow$ associated $b\bar{b}\,(tb)$ $\qquad$ low $M_{1/2}$

singlet-like $\rightsquigarrow$ inaccessible

Higgs cross-over region: two nearly **degenerate**, **same couplings** states

sum behaves as ONE SM Higgs - resolve $\gamma\gamma$ peak?

cNMSSM searches at the ILC?

cNMSSM production @ ILC

- **500 GeV:** $\chi^0_{1,2}$, $\tilde{l}_R$, $\tilde{\tau}_R$ $\quad (M_{1/2} \lesssim 500$ GeV)
- **1 TeV:** $\chi^0_{1-3}, \chi^\pm_1$, $\tilde{l}_R$, $\tilde{\tau}_R$, $\tilde{l}_L$
- **multi-TeV:** all cNMSSM states

- **Detection** of $\tilde{\tau}_1$ (nearly **degenerate with LSP**)

- Accurate **determination** of SUSY masses (via threshold scans)

- If c.m. energy $\lesssim 1$ TeV, only **lighter h_i and a_i accessible**
  - large $h^0_1 - h^0_2$ singlet/doublet mixing (nearly degenerate states)

    Higgs-strahlung process, **~ 100 MeV** Higgs mass **resolution**
  - Higgs-to-Higgs decays: $h^0_2 \to h^0_1 h^0_1$ in $e^+e^- \to h^0_2\,Z \to \mu^+\mu^-\,b\,\bar{b}\,b\,\bar{b}$
  - Accessible singlet-like a^0_1 in $e^+e^- \to h^0_2\,a^0_1 \to b\,\bar{b}\,b\,\bar{b}$

Concluding remarks & outlook

- Why the NMSSM?? **simple** and very attractive **SUSY extension** of the SM

  A lot of work to be done (especially experimental simulations)!

- cNMSSM allowed parameter space: described by **ONE parameter!**

  Very low m_0, small A_0 values, and $M_{1/2} \lesssim 1$ TeV; $\tan\beta \sim 30$

  Satisfy observed Higgs excesses at LEP and $(g-2)_\mu$ deviation from SM

- cNMSSM - different spectra from cMSSM!

  $m_{\tilde{g}} \gtrsim m_{\tilde{q}}$; $\boldsymbol{\tilde{\tau}_1}$ in **all** decay **cascades** (possibly long lived)

- **Dark matter** detection prospects: well below experimental capabilities ...

- **Testable** at LHC, but **ILC required** for precision measurements

Additional slides

NMSSM: $\tilde{\chi}^0$ and scalar Higgs mass matrices

CP-even Higgs

$$\mathcal{M}^2_{S,11} = M_Z^2 \cos^2\beta + \lambda s \tan\beta (A_\lambda + \kappa s)$$
$$\mathcal{M}^2_{S,22} = M_Z^2 \sin^2\beta + \lambda s \cot\beta (A_\lambda + \kappa s)$$
$$\mathcal{M}^2_{S,33} = 4\kappa^2 s^2 + \kappa A_\kappa s + \frac{\lambda}{s} A_\lambda v_1 v_2$$
$$\mathcal{M}^2_{S,12} = \left(\lambda^2 v^2 - \frac{M_Z^2}{2}\right) \sin 2\beta - \lambda s (A_\lambda + \kappa s)$$
$$\mathcal{M}^2_{S,13} = 2\lambda^2 v_1 s - \lambda v_2 (A_\lambda + 2\kappa s)$$
$$\mathcal{M}^2_{S,23} = 2\lambda^2 v_2 s - \lambda v_1 (A_\lambda + 2\kappa s)$$

$$h_a^0 = S_{ab} H_b^0$$

CP-odd Higgs

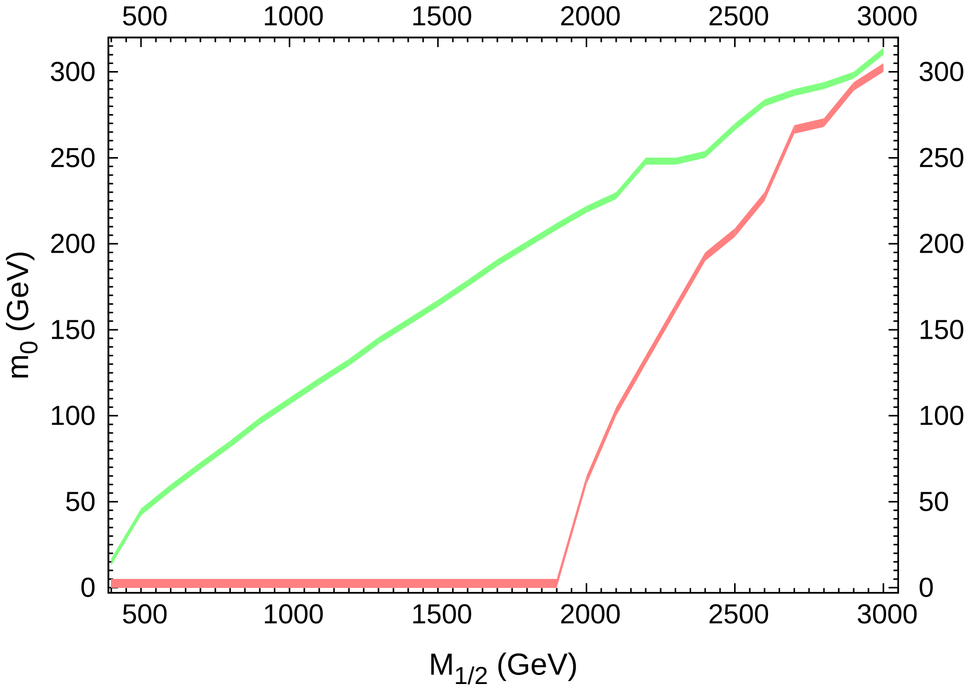
$$\mathcal{M}^2_{P,11} = \frac{2\lambda s}{\sin 2\beta} (\kappa s + A_\lambda)$$
$$\mathcal{M}^2_{P,22} = \lambda \left(2\kappa + \frac{A_\lambda}{2s}\right) v^2 \sin 2\beta - 3\kappa A_\kappa s$$
$$\mathcal{M}^2_{P,12} = \lambda v (A_\lambda - 2\kappa s)$$

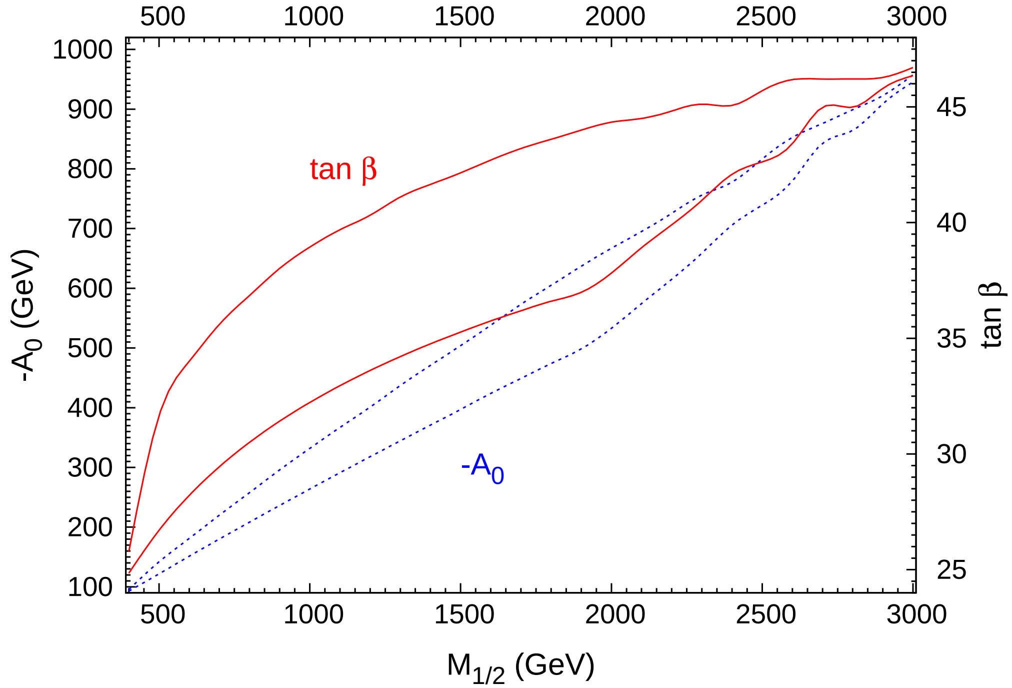
$$a_i^0 = P_{ij} P_j^0$$

Neutralino Sector

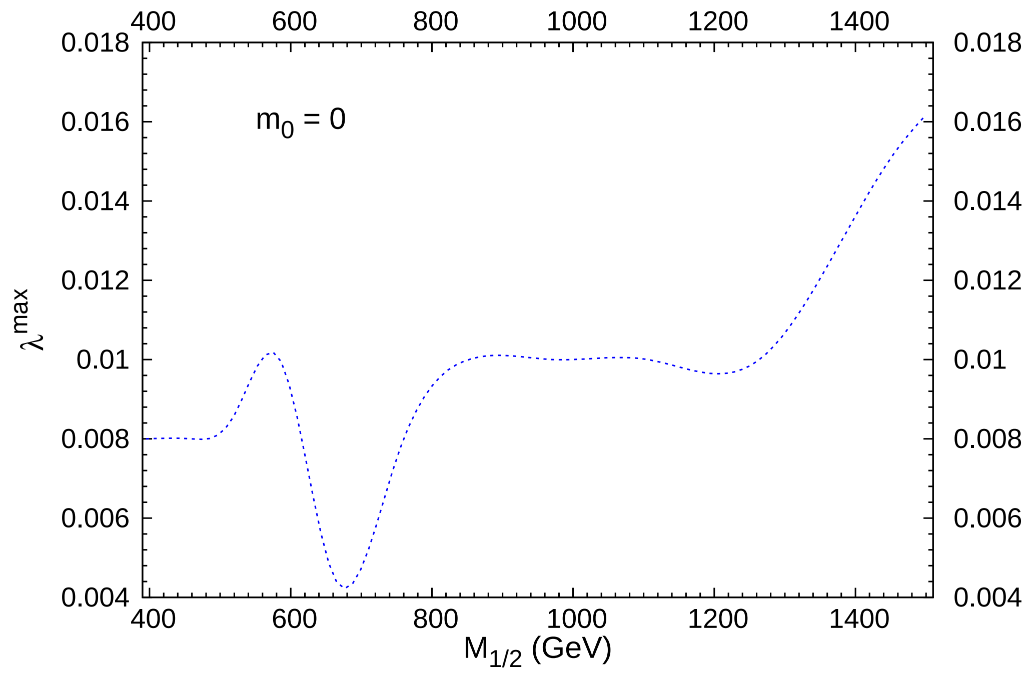
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta & 0 \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta & 0 \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\lambda s & -\lambda v_2 \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\lambda s & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa s \end{pmatrix}$$

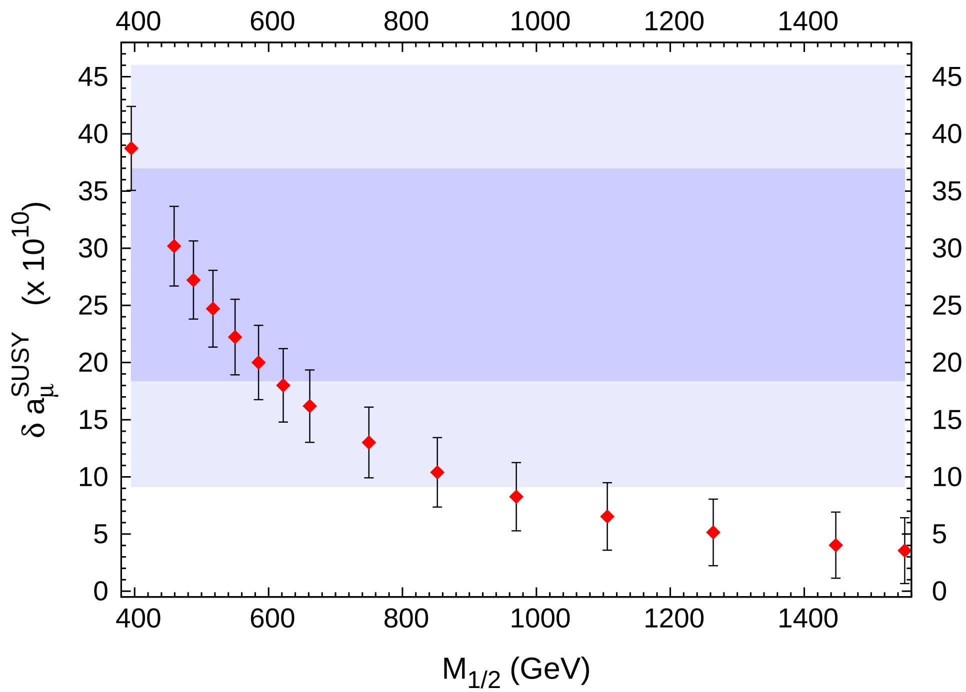
Ranges





Additional phenomenology





Tables: Spectra

	P1	P2
$M_{1/2}$ (GeV)	500	1000
m_0 (GeV)	0	0
A_0 (GeV)	-122	-263
$\tan\beta$	26.7	32.2
μ_{eff} (GeV)	640	1185
M_2 (GeV)	390	790
$m_{h_1^0}$ (GeV)	86	119
$m_{h_2^0}$ (GeV)	116	187
$m_{h_3^0}$ (GeV)	610	1073
$m_{a_1^0}$ (GeV)	149	323

	P1	P2
$M_{1/2}$ (GeV)	500	1000
$m_{\chi_1^0}$ (GeV)	122	264
$m_{\chi_2^0}$ (GeV)	206	427
$m_{\chi_3^0}$ (GeV)	388	802
$m_{\chi_{4,5}^0}$ (GeV)	645	1190
$m_{\chi_1^\pm}$ (GeV)	388	801
$m_{\chi_2^\pm}$ (GeV)	658	1198
$m_{\tilde{g}}$ (GeV)	1150	2187
$m_{\tilde{u}_L}$ (GeV)	1044	1973
$m_{\tilde{u}_R}$ (GeV)	1007	1895
$m_{\tilde{t}_1}$ (GeV)	795	1539
$m_{\tilde{t}_2}$ (GeV)	997	1810
$m_{\tilde{b}_1}$ (GeV)	931	1760
$m_{\tilde{b}_2}$ (GeV)	983	1817
$m_{\tilde{e}_L}$ (GeV)	334	654
$m_{\tilde{e}_R}$ (GeV)	190	370
$m_{\tilde{\nu}_l}$ (GeV)	325	650
$m_{\tilde{\tau}_1}$ (GeV)	127	269
$m_{\tilde{\tau}_2}$ (GeV)	343	647
$m_{\tilde{\nu}_\tau}$ (GeV)	318	631

	P1′	P2′
$M_{1/2}$ (GeV)	500	1000
m_0 (GeV)	40	107
A_0 (GeV)	-137	-327
$\tan\beta$	30.2	38.4
μ_{eff} (GeV)	642	1192
M_2 (GeV)	390	791
$m_{h_1^0}$ (GeV)	64	116
$m_{h_2^0}$ (GeV)	116	127
$m_{h_3^0}$ (GeV)	588	989
$m_{a_1^0}$ (GeV)	149	333
$m_{\chi_1^0}$ (GeV)	107	226
$m_{\tilde{\tau}_1}$ (GeV)	112	235

Tables: Production and Decays

σ (pb)	P1	P2
$\tilde{g}\,\tilde{g}$	9.5×10^{-2}	2.14×10^{-4}
$\tilde{g}\,\tilde{q}$	0.668	4.28×10^{-3}
$\tilde{q}\,\tilde{q}$	0.436	9.21×10^{-3}
$\tilde{q}\,\tilde{q}^*$	0.221	1.64×10^{-3}
$\tilde{t}_1\,\tilde{t}_1^*$	3.69×10^{-2}	2.63×10^{-4}
$\tilde{l}_L\,\tilde{l}_L^*$	3.4×10^{-3}	1.62×10^{-3}
$\tilde{l}_R\,\tilde{l}_R^*$	1.17×10^{-2}	8.87×10^{-4}
$\tilde{\nu}_l\,\tilde{\nu}_l^*$	3.58×10^{-3}	1.53×10^{-4}
$\tilde{\tau}_1\,\tilde{\tau}_l^*$	4.8×10^{-2}	3.46×10^{-3}
$\chi_2^0\,\chi_2^0$	1.1×10^{-3}	6.22×10^{-5}
$\chi_2^0\,\chi_3^0$	1.73×10^{-4}	8.67×10^{-6}
$\chi_2^0\,\chi_1^\pm$	5.37×10^{-4}	6.53×10^{-5}
$\chi_3^0\,\chi_3^0$	1.79×10^{-3}	5.74×10^{-5}
$\chi_3^0\,\chi_1^\pm$	6.51×10^{-2}	7.49×10^{-3}
$\chi_1^+\,\chi_1^-$	3.53×10^{-2}	1.17×10^{-3}

BR (%)	P1	P2
$\tilde{g} \to \tilde{q}_L\,\bar{q}$	17.7	14.4
$\tilde{g} \to \tilde{q}_R\,\bar{q}$	33.6	27.5
$\tilde{g} \to \tilde{b}_1\,\bar{b}$	16.5	12.8
$\tilde{g} \to \tilde{b}_2\,\bar{b}$	10.9	10.3
$\tilde{g} \to \tilde{t}_1\,\bar{t}$	21.2	22.4
$\tilde{g} \to \tilde{t}_2\,\bar{t}$	–	12.5
$\tilde{q}_L \to \chi_3^0\,q$	31.7	32.3
$\tilde{q}_L \to \chi_1^\pm\,q'$	62.7	64.3
$\tilde{q}_R \to \chi_2^0\,q$	99.7	99.9
$\tilde{l}_L \to \chi_2^0\,l$	100	100
$\tilde{l}_R \to l\,\tilde{\tau}_1\,\tau$	$\gtrsim 95$	$\gtrsim 99$
$\tilde{\nu}_l \to \chi_2^0\,\nu_l$	100	100
$\tilde{\nu}_\tau \to \chi_2^0\,\nu_\tau$	13.8	6.8
$\tilde{\nu}_\tau \to \tilde{\tau}_1\,W$	86.2	93.2

BR (%)	P1	P2
$\chi_2^0 \to \tilde{\tau}_1\,\tau$	88.3	74.3
$\chi_2^0 \to \tilde{l}_R\,l$	11.7	25.7
$\chi_3^0 \to \tilde{l}_L\,l$	22.1	28.4
$\chi_3^0 \to \tilde{\nu}_l\,\nu_l$	27.1	29.2
$\chi_3^0 \to \tilde{\tau}_1\,\tau$	24.9	8.8
$\chi_3^0 \to \tilde{\tau}_2\,\tau$	6.9	14.8
$\chi_3^0 \to \tilde{\nu}_\tau\,\nu_\tau$	16.9	18.3
$\chi_1^\pm \to \tilde{\nu}_l\,l$	29.3	29.9
$\chi_1^\pm \to \tilde{l}\,\nu_l$	20.8	27.8
$\chi_1^\pm \to \tilde{\nu}_\tau\,\tau$	18.4	18.9
$\chi_1^\pm \to \tilde{\tau}_1\,\nu_\tau$	24	8.7
$\chi_1^\pm \to \tilde{\tau}_2\,\nu_\tau$	–	14.3